Characterization of North Atlantic Right-Whale (*Eubalaena glacialis*) Sounds in the Bay of Fundy

Angelia S. M. Vanderlaan, Alex E. Hay, and Christopher T. Taggart

***Abstract*—Hydrophone recordings, made in the presence of North Atlantic right whales (*Eubalaena glacialis*) in the Bay of Fundy during the daytime in July 1999, are used to determine the characteristics of the recorded sounds. A spectrogram-based method was implemented to discriminate whale sounds from background noise and the time-frequency envelope of the primary harmonic in the spectrogram was used as the basis for sound characterization. Sounds were typically (82%, $n = 45$) in the 300- to 600-Hz range with up- and downsweeping modulations. Lower (<200 Hz) and higher (>900 Hz) frequency sounds were relatively rare. Most sounds were frequency modulated, with 95% of the observed instantaneous relative frequency variation being within $\pm 4.5\%$ of the mean peak frequency. Harmonics were observed in 18% of the sounds. The average sound duration was 0.42 s $\pm$ 0.26 SD. The sounds occurred at a rate of between 0.3 and 0.7 min^{-1}. The time intervals between adjacent sounds (2–700 s) were not randomly distributed. The number of sounds occurring among different waiting times did not reflect a Poisson distribution and a clustering of sounds (2 to 5 cluster^{-1}) was observed. The sound characteristics are compared to those documented elsewhere and as reported for the southern right whale.**

***Index Terms*—Acoustic, characterization, frequency, monitoring, right whale, sound.**

I. INTRODUCTION

THE North Atlantic right whale (*Eubalaena glacialis*) is the most endangered large whale in the world [1]–[3]. There are now <350 individuals in the only extant population [4], [5], which is in negative growth due to high human-induced mortality. Ship strikes accounted for 35.5% (16/45) of the documented North Atlantic right whale mortality between 1970 and 1999 [5]. Estimates of extinction time for the species are as short as ≈200 years [3].

The majority of the population spends the summer and autumn feeding in the Grand Manan Basin region of the Bay of Fundy. This habitat, which is a Canadian Right Whale Conservation Area (Fig. 1), also overlaps an internationally designated shipping lane. Being a relatively small area where the whales are typically concentrated, there is a resultant increase in the probability of collision with ships. Commercial fishing activity in the region presents an additional threat to the whales through entanglement in fishing gear [3]. It may be possible to reduce ship-strike risk and the potential for gear entanglement by using passive acoustic techniques to locate whale sounds and to thereby track whale groups and perhaps individuals. Whether obtained as part of a system for providing advance warning to ships of whale locations relative to the shipping lane or as a complement to a long-term monitoring program, passive acoustic systems have the potential to significantly increase the available data on right-whale spatial distributions in the area. Such data would be extremely useful for better identifying the times and places where ship-strike and gear-entanglement probabilities are elevated.

Passive acoustic techniques have been used previously to investigate the migration of several whale species [6]–[8] and to estimate population size [9]–[11] and seasonal variations in habitat occupation in the northwest (NW) Atlantic [12]. Passive acoustic monitoring has been proposed for the NW Atlantic right-whale population [13]–[15]. However, acoustic monitoring requires knowledge of the characteristics of the sounds produced by the whales. Southern right-whale sounds have been characterized [16]–[20] and although North Atlantic right-whale sounds have been described as similar to the southern variant [21]–[23], there is a paucity of information on North Atlantic right-whale sound characteristics. Furthermore, as Clark has shown that the types of sounds produced by southern right whales are a function of their behavior, it is possible that the spectral characteristics and rate of sound production by northern right whales may vary seasonally and with their habitat. To our knowledge, the only right-whale sounds described for the Bay of Fundy are those reported by Spero [24] in an abstract and more recently by Matthews *et al.* [25].

In summer 1999, we carried out a pilot study designed to record and compile data on the sounds produced by the right whale in the Bay of Fundy as a first step toward assessing the feasibility of passive acoustic monitoring in this area. The primary objective of this paper is to summarize the spectral and time-domain characteristics of the right-whale sounds recorded. The paper is organized as follows. First, the study area and methods are described, followed by an explanation of the data-analysis procedures. The results presented include mean peak frequency of the primary harmonic, frequency modulation and variation, durations of the sounds, and the time intervals between consecutively received sounds. The implications that these sound properties and their associated statistics may have

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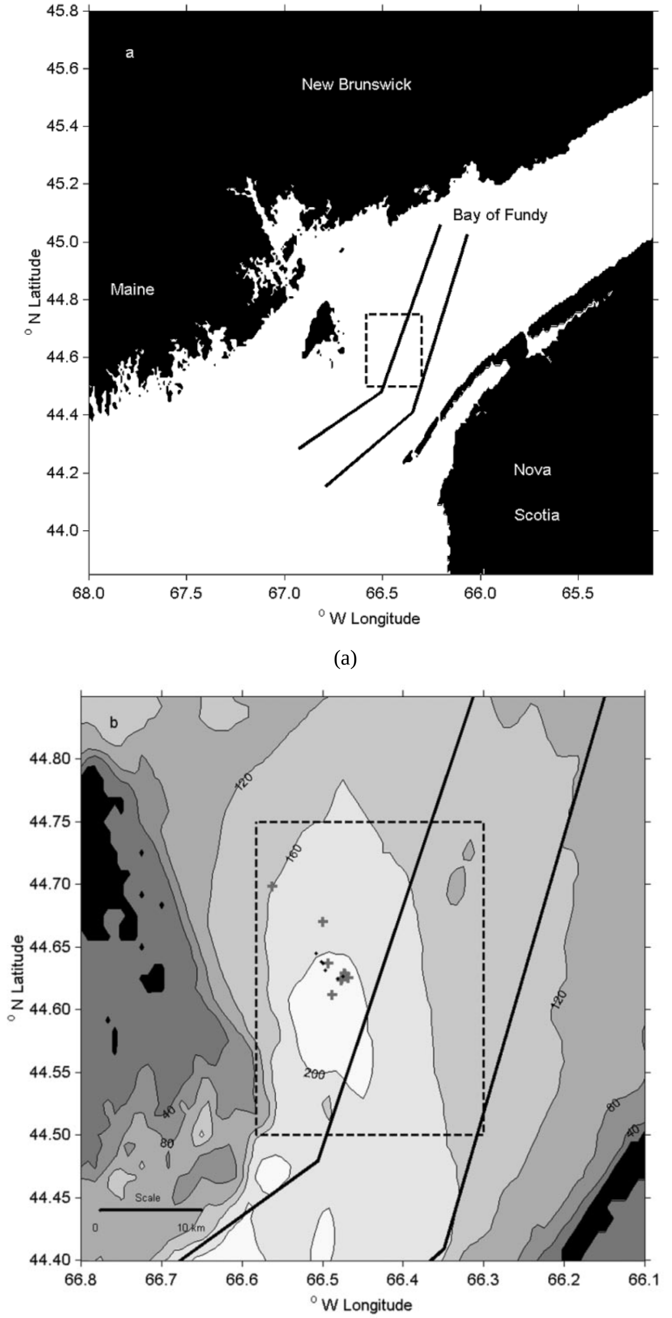

(a)

(b)

Fig. 1. Study area (land is black). (a) Bay of Fundy; shipping lane (heavy solid line) and the right whale conservation area (dashed line). (b) Grand Manan Basin bathymetry (40-m isobath intervals, solid line), hydrophone recording locations (crosses), and locations of visually identified right whales (filled circles) on July 29, 1999.

for passive acoustic monitoring system are then presented. The potential for localizing the sounds is presented elsewhere by Desharnais *et al.* [13], [26].

II. METHODS

A. Hydrophone Recordings

The recordings were made in the Grand Manan Basin region of the Bay of Fundy, Canada (Fig. 1), in calm conditions with moderate to heavy fog from a drifting 10-m research vessel (RV *Neirid*, New England Aquarium, Boston, MA), during a 4-h period in the early afternoon [12:30 to 15:50 coordinated universal time (UTC)] of July 29, 1999. Sounds were received using a Cetacean Research Technology hydrophone (12–35-kHz bandwidth) deployed at 6–10-m depth and recorded on a Sony Portable MZ-R50 MiniDisc recorder (44.1 kHz sampling frequency). Approximately 2 h of data were recorded at eight different locations [Fig. 1(b)]. A total of eight tracks (one per location) were recorded. The median track duration was 7.5 min (1.5–41-min range). Whale sounds occurred on five of the eight tracks.

Approximately 60 right whales were known to be resident in the immediate area one week prior to our arrival (P. Hamilton, New England Aquarium, personal communication). Individual right-whale locations (nine visual sightings, six of which were different individuals) and hydrophone-deployment locations were determined using the *Neirid*'s global positioning system [(GPS); Fig. 1(b)]. If right whales appeared during a recording session and subsequently departed from the immediate area, the vessel moved to a new location where whales were present (either seen or heard when blowing and subsequently seen). No other whale species were observed in the immediate area, with the exception of two minke (*Balaenoptera acutorostrata*) whales observed earlier in the day $\sim$22 km from the recording locations.

The audio analog output from the MiniDisc was acquired on a PC–NT computer using a SoundBlaster card. During playback for digitization, the MiniDisc output was electronically band-pass filtered (100-Hz and 2-kHz cutoff frequencies with 40 dB per decade rolloff beyond the passband). The band-pass filter reduced noise, especially the high noise levels below 100 Hz that might have otherwise compromised the dynamic range of the analog-to-digital converter. The recordings were digitized using Goldwave (Ver. 4.1) at a sampling frequency of 5000 Hz with 16-bit resolution. Two channels were digitized: the analog sound signal from the MiniDisc and a manually activated voltage-pulse used to event-mark aurally detected whale sounds in the recordings.

B. MiniDisc Assessment

The MiniDisc records a digital data stream using a proprietary compression algorithm. Laboratory tests were carried out to check for possible distortion of the input signal resulting from the compression technique, in the frequency range of our recordings. Test signals were produced using a Hewlett-Packard 3312 function generator, in both continuous-wave (CW) and pulsed modes. The function generator output was recorded on the MiniDisc and then acquired on the personal computer (PC) in the same manner as the Bay of Fundy recordings. The frequencies generated ranged from 100 to 2500 Hz in 100-Hz increments for the CW tests and 100 Hz to 1300 Hz for the pulse tests. The pulse durations were 10 and 60 ms. The root mean square (RMS) amplitudes of the recorded pulses varied by less than ± 1 dB over the range of 100 to 1300 Hz; the amplitudes of the recorded CW signals were flat (less than ± 0.1 dB) between 300 and 1700 Hz, with some rolloff at both the higher and lower frequency ends (2 dB at 100 Hz and 1 dB at 2000 Hz). These results indicate that the compression algorithm would not have compromised the frequency characteristics of the whale sound recordings reported here.

C. Processing

A series of processing steps was implemented to discriminate the whale sounds from the background noise prior to subsequent analyses. As outlined below, these steps yielded the time–frequency envelope of the "primary" harmonic: that is, for sounds containing harmonics, the most prominent harmonic in the spectrogram, usually the fundamental; for sounds without obvious harmonics (the majority of cases here), the sole harmonic present, presumably the fundamental.

Power spectral densities were calculated with a frequency resolution of 5 Hz and a time resolution of 6.4 ms to create a spectrogram of each sound. The digitized signal for the time segment corresponding to the spectrogram was replayed for aural confirmation and the approximate peak frequency (f^*) of the primary harmonic (defined above) was visually estimated from the spectrogram. The signal was then digitally band-passed filtered between $0.75f^*$ and $1.8f^*$ and reexamined (visually and aurally) to ensure that it had been fully captured within this passband.

The time segment of the spectrogram starting ~ 2 s prior to the visual start and ending ~ 2 s following the visual end of the primary harmonic was saved, spanning the full frequency range [(0–2500) Hz]. These spectrogram segments were further reduced to a "box" (Fig. 2) with an approximate frequency range of 150 to 300 Hz centered on the frequency of maximum sound intensity $f_m(t)$, defined below. This box also further isolated the primary harmonic in time, beginning ~ 0.1 s prior to the visual start and terminating ~ 0.1 s following the visual end of the sound in the spectrogram.

The frequency corresponding to the maximum spectral density for each time within the box was determined and designated $f_m(t)$, where t is the time [Fig. 2(b)]. A frequency band 25 Hz wide and centered on $f_m(t)$ was defined. Then, the peak frequency, $f_p(t)$, was determined from the spectral density-weighted mean frequency across the 25-Hz band, given by

$$f_p = \frac{\int_{f_1}^{f_2} f^* S_{\mathrm{pp}}\, df}{\int_{f_1}^{f_2} S_{\mathrm{pp}}\, df} \tag{1}$$

where f_1 is ($f_m - 12.5$ Hz), f_2 is ($f_m + 12.5$ Hz), and S_{pp} is the spectral density [Fig. 2(b)]

The intensity of the primary harmonic (signal intensity) was computed by integrating the spectral densities across the 25-Hz band and the total intensity (signal+noise) was similarly determined by integrating over the full range of frequencies within the box. The difference between the total intensity and the signal intensity provided the noise-floor estimate. Thus, as shown in Fig. 2(c), the start and end of the primary harmonic within a box could be defined as the times when the signal rose above and fell below the noise. This procedure yielded an estimate of the time-varying local noise level in the spectrogram box and a corresponding estimate of the signal-to-noise ratio for the primary harmonic of each whale sound.

Determining the start and end of a sound using the time-varying noise level method, while having the advantages of being both objective and easily implemented, does have some effect on the results presented below for the durations and time separation between whale sounds (i.e., a sound that was in fact continuous, but rose above and fell below the noise level would, by this method, be classified as two or more distinct sounds, potentially of different mean peak frequencies, each of shorter duration.

Most data processing was done using MATLAB [27] unless otherwise noted.

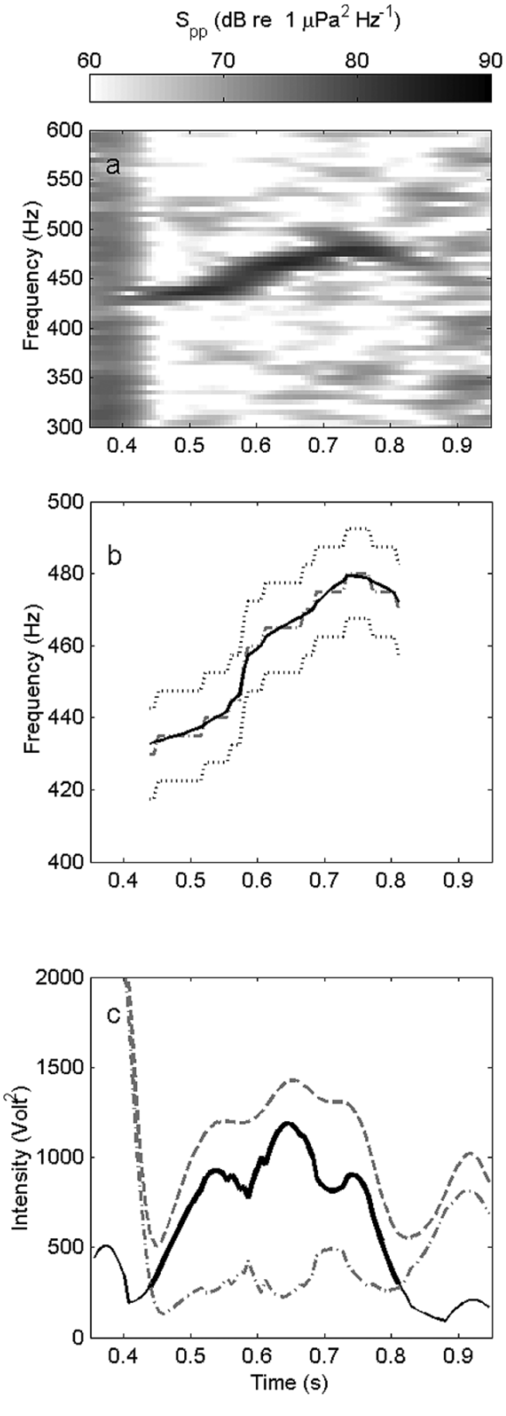

Fig. 2. Primary harmonic extraction procedure. (a) Spectrogram "box" showing primary harmonic of a right-whale sound; (b) the frequency of maximum intensity $(f_m(t), \text{-·-})$ centered within the 25-Hz band (····), the peak frequency $(f_p(t)$—; and (c) total intensity (- - -), signal intensity (—), and noise intensity (-.-). The thick solid line denotes the duration of this sound (signal-to-noise ratio > 1).

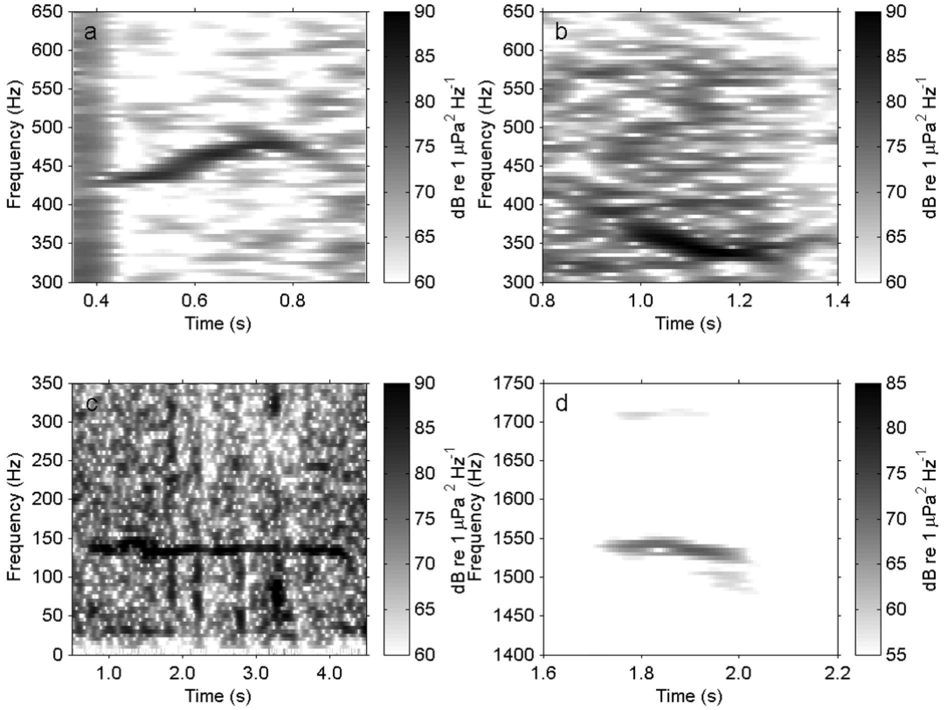

Fig. 3. Example spectrograms of right-whale primary harmonics: (a) upsweeping modulation, mean peak frequency $\bar{f}_p = 459$ Hz; (b) downsweeping modulation $\bar{f}_p = 347$ Hz; (c) low-frequency unmodulated sound $\bar{f}_p = 135$ Hz (note the frequent occurrence of broad-band noise typically lasting 0.15 s; e.g., at 1.75 and 3.25 s); and (d) rare high-frequency sound $\bar{f}_p = 1536$ Hz (note that the relative intensity is greatly reduced compared to the majority of sounds (a) and (b) in the 340–600-Hz band).

D. *Frequency and Time-Domain Features*

For the primary harmonic, we defined the instantaneous frequency variation δ_p as

$$\delta_p(t) = f_p(t) - \bar{f}_p \tag{2}$$

and the instantaneous relative-frequency variation Δ_p as

$$\Delta_p(t) = \delta_p(t)/\bar{f}_p \tag{3}$$

where $\bar{f}_p$ is the mean peak frequency (the overbar indicates a time average). The total variation is defined as the difference between the maximum and minimum values of $\delta_p(t)$; similarly, the total relative variation is then defined to be the difference between the maximum and minimum values of $\Delta_p(t)$.

Sounds were examined for harmonic structure by visual inspection of the spectrograms before “boxing,” as well as by examining frequency versus spectral density (e.g., spectral maxima at or near harmonic frequencies relative to $f_p(t)$).

Time-on-track (the time t_n that sound n occurred on a given track), also referred to as the waiting time until the nth sound, for all tracks was aurally determined (±1 s) using the original MiniDisc recordings. Clustering analyses of sounds were performed by both including the time to the first sound on track and by using only the difference between the time on track and the time to the first sound on track $(t_n - t_1)$.

E. *Statistical Analysis*

Sound characteristics (mean peak frequency, peak-frequency variation and duration of each sound, and time between sounds) were imported to Number Cruncher Statistical Software (NCSS) [28] to provide basic descriptive statistics and analyses of distributions. Using varying window widths, the number of events (sounds) was compared to a Poisson distribution using a maximum-likelihood-estimation (MLE) function for goodness of fit. The Greenwood statistic [29] was used to determine if the time intervals between events were exponentially distributed (i.e., do event times constitute a Poisson process?) and to test for uniformity in the time between sounds.

III. RESULTS

Fifty-three sounds were identified as right-whale sounds from the two hours of recording. Of these, 45 were considered suitable for extraction and analysis. In general, the right whales produced a variety of sounds that were typically in the 300–600-Hz range with up- [Fig. 3(a)] and downsweep [Fig. 3(b)] modulations. Lower- [Fig. 3(c)] and higher- [Fig. 3(d)] frequency sounds were relatively rare.

A. *Mean Peak Frequencies*

The mean peak frequency $(\bar{f}_p)$ ranged from 65 to 1540 Hz (Fig. 4), with the majority (37/45) occurring between 300 and 600 Hz with a median of 484 Hz (Fig. 4, Table I). Two sounds that were aurally detected below 200 Hz (Fig. 4, Table I; see also Desharnais *et al.* [26]) were analyzed as two and three separate sounds, respectively, due to our use of the noise-floor criterion described above, when in fact each may have been one continuous sound. This lower range of sounds accounted for 11% (5/45) of the sounds analyzed. The remaining 7% occurred at frequencies >900 Hz and covered a relatively broad frequency

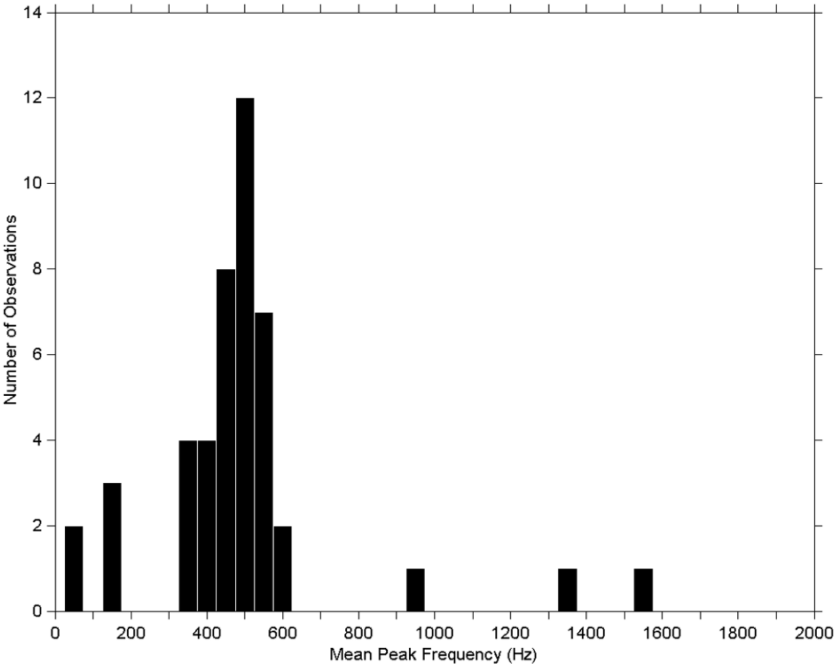

Fig. 4. Distribution (number of observations) of mean peak frequencies $\bar{f}_p$ for a series of North Atlantic right-whale sounds $(n = 45)$. The majority of the sounds occur between 340 and 600 Hz (frequency-class width = 50 Hz).

TABLE I

DEFINING STATISTICS FOR THE "PRIMARY" HARMONIC OF NORTH ATLANTIC RIGHT-WHALE (*EUBALAENA GLACIALIS*) SOUNDS IN THE BAY OF FUNDY FOR LOW-, INTERMEDIATE-, AND HIGH-FREQUENCY BANDS: MEAN PEAK FREQUENCY $(\bar{f}_p)$, DURATION, AND TOTAL RELATIVE VARIATION $(\Delta_p \max - \Delta_p \min)$

'Primary' Harmonic Frequency Band (Hz)	n	$\overline{f_p}$ (Hz) mean ± SD [range]	Duration (s) mean ± SD [range]	Δ_p max− Δ_p min mean ± SD [range]
< 200	5	108 ± 36	0.57 ± 0.42	0.0997 ± 0.0890
		[65-140]	[0.25-1.26]	[0.0227 0.2451]
200-900	37	473 ± 66	0.40 ± 0.23	0.0565 ± 0.0402
		[340 -600]	[0.08 – 1.18]	[0.0034 0.1546]
> 900	3	1276± 308	0.32 ± 0.26	0.0077 ± 0.0029
		[930 - 1540]	[0.09-0.60]	[0.0044 0.0100]

range (Fig. 4, Table I). Two sounds at even higher frequencies (~1600 and ~1900 Hz) had intensities insufficient for analysis.

B. Duration

Individual sound durations ranged from 0.08 to 1.26 s (Fig. 5, Table I) with a mean of 0.42 s $\pm$ 0.26 s SD ($\mathrm{median} = 0.36$ s, $\mathrm{geometric\ mean} = 0.35$ s). Lower frequency sounds (<200 Hz) tended to be shorter than those estimated by spectrogram inspection; likely a result of the noise-floor criterion.

C. Frequency Modulation and Total Frequency Variation

Frequency modulations in the form of up- and downsweeps, or both, were observed in almost all sounds. The total frequency variation for the primary harmonics varied between 1 and 76 Hz (3.3 and 15.5% of $\bar{f}_p$, respectively). The distribution of $\Delta_p(t)$, the instantaneous relative frequency variation, is presented in Fig. 6; the minimum observed value was -0.2 (maximum 0.1). The interval [-4.6 4.5%] characterized 95% of the observed frequency variation relative to the mean peak frequency.

D. Multifrequency Sounds

Harmonics (frequencies at integer multiples of the fundamental) and nonharmonic frequency bands (usually) above the primary harmonic were observed in 27% of the sounds. Second harmonics were observed in 9% (4/45) of the sounds and another 9% contained each of the second, third, and fourth harmonics (Fig. 7). Features with time-frequency envelopes similar to the primary but not obviously part of a harmonic sequence were observed in the remaining 9%. These nonharmonic bands were, in some cases, in the approximate range of a higher harmonic band (e.g., fourth harmonic in three different sounds) based on calculations using the mean peak frequency and the initial and final frequency of the primary harmonic, but the second and third harmonics were not detected.

E. Sound Intervals and Clusters

The interval between consecutive sounds ranged from 2 to 736 s (Fig. 8). The longest waiting time for the first sound on a given track (t_1) was 1013 s. The Greenwood statistic was used

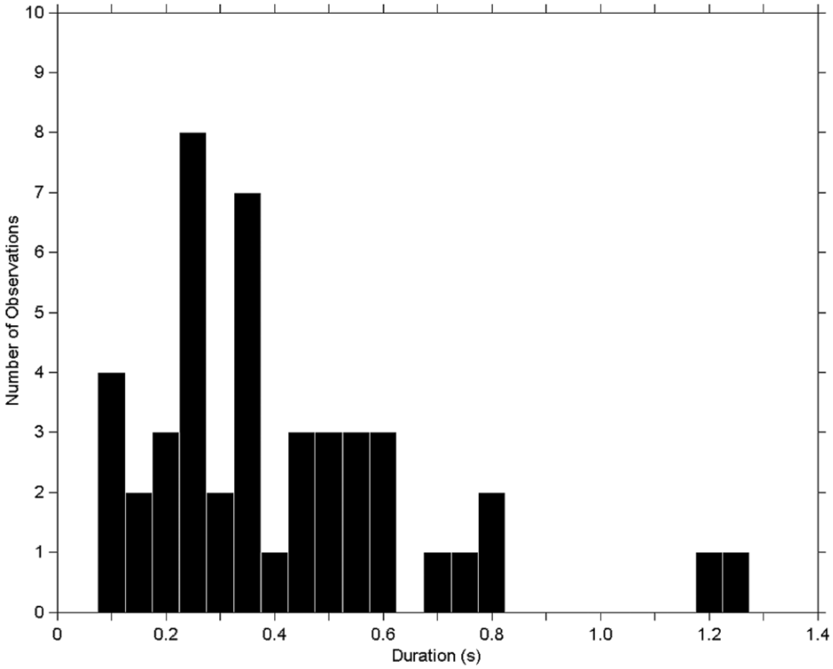

Fig. 5. Distribution (number of observations) of the duration (s) of North Atlantic right-whale sounds $(n = 45)$ showing a range between 0.08 and 1.26 s $(\mathrm{mean} = 0.42$ s $\pm\ 0.26$ s SD; $\mathrm{geometric\ mean} = 0.35$ s; $\mathrm{duration\text{-}class\ width} = 0.05$ s).

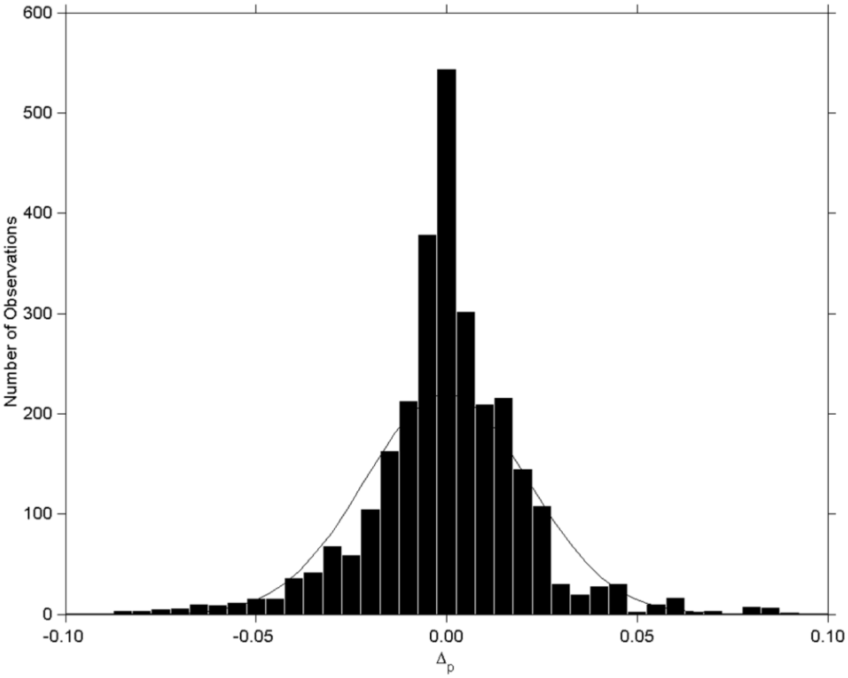

Fig. 6. Distribution of instantaneous relative frequency variation Δ_p, (3) for North Atlantic right-whale sounds $(\Delta_p\ \mathrm{class\ width} = 0.005)$. Two observations (at $\Delta_p = -0.2$) are not shown. Solid line represents the normal distribution with zero mean and the observed variance $(n = 45)$.

to reject the hypothesis that the intervals between sounds were exponentially distributed $(p \ll 0.01)$ and that the intervals between sounds were not uniformly distributed.

The time on track for consecutive sounds showed a step-like function of large (200–400 s; i.e., sound sequences two, seven, nine, and 13, Fig. 9) intervals between consecutive sounds that separated clusters of consecutive sounds with relatively short (10–50 s) intervals (Fig. 9). If the probability of a sound occurring was small and occurred randomly, it is reasonable to expect the times on track to exhibit a Poisson distribution. The MLE goodness-of-fit tests indicated that the number of sounds among different intervals did not reflect a Poisson distribution $(p \ll 0.001)$. Thus, the sounds we recorded did not occur in a random fashion. Further, the probability of hearing (recording) a whale sound was not small. Using a tentative definition of a North Atlantic right-whale sound cluster being one where

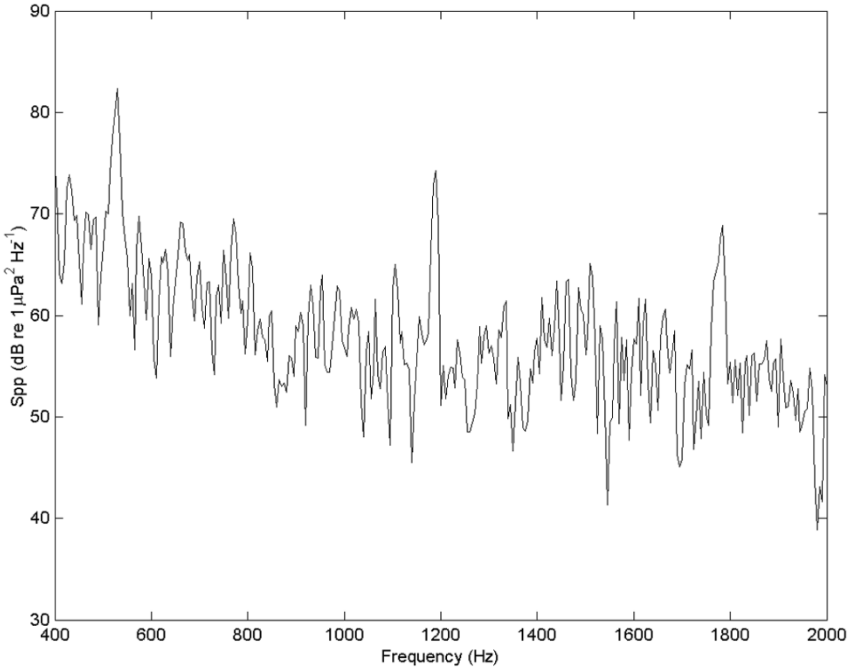

Fig. 7. Power spectrum of a multifrequency right-whale sound showing the fundamental near 600 Hz, second and third harmonics at ~ 1200, ~ 1800 Hz, respectively (fourth harmonic observed at ~ 2400 Hz is not shown). Note the background noise level decreasing from ~ 70 to ~ 50 dB between 400 and 2000 Hz and the 15–20-dB signal-to-noise ratios of the spectral peaks corresponding to the fundamental and its harmonics.

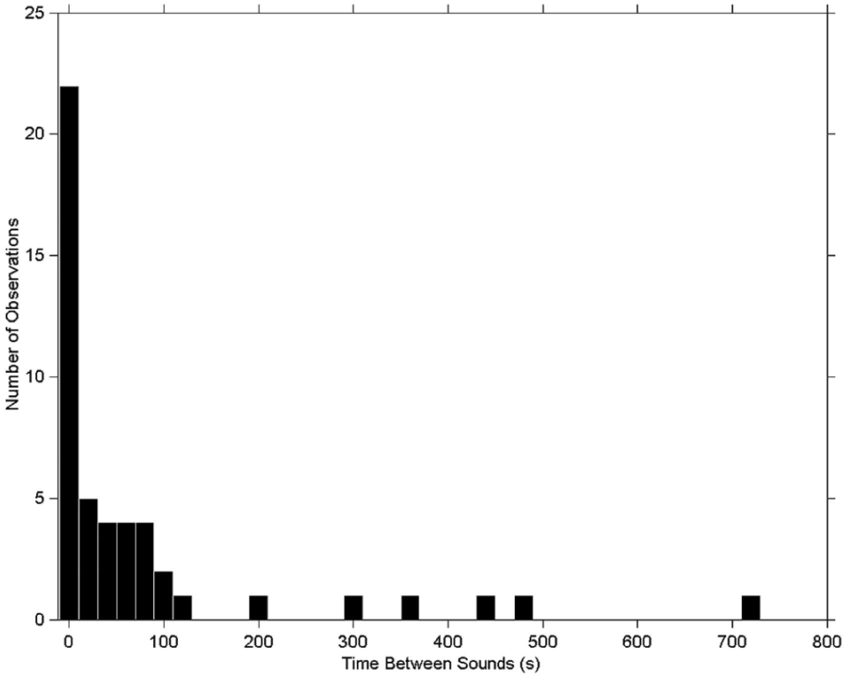

Fig. 8. Distribution (number of observations) of the time between North Atlantic right-whale sounds (intervals). A large number of small intervals between adjacent sounds and the presence of larger intervals (≈ 700 s) indicate clustering through time. Sound interval $\mathrm{class\ width} = 20$ s.

sounds occur within 15 s of each other, we observed 11 sound clusters, each containing between two and five sounds, within the 2-h recording period.

IV. DISCUSSION

While there are very few published results characterizing North Atlantic right-whale sounds, our results are consistent with the Schevill and Watkins [30] analog recording of North Atlantic right-whale sounds for which the one spectrogram presented had a fundamental frequency of ~ 400 Hz and with the more-recent work of Matthews *et al.* [25] who described a 50–500-Hz range for frequency-modulated tonal sounds. Further, the mean peak frequencies of the primary harmonic reported here and the several sounds containing harmonic structure are also similar to right-whale sounds described by

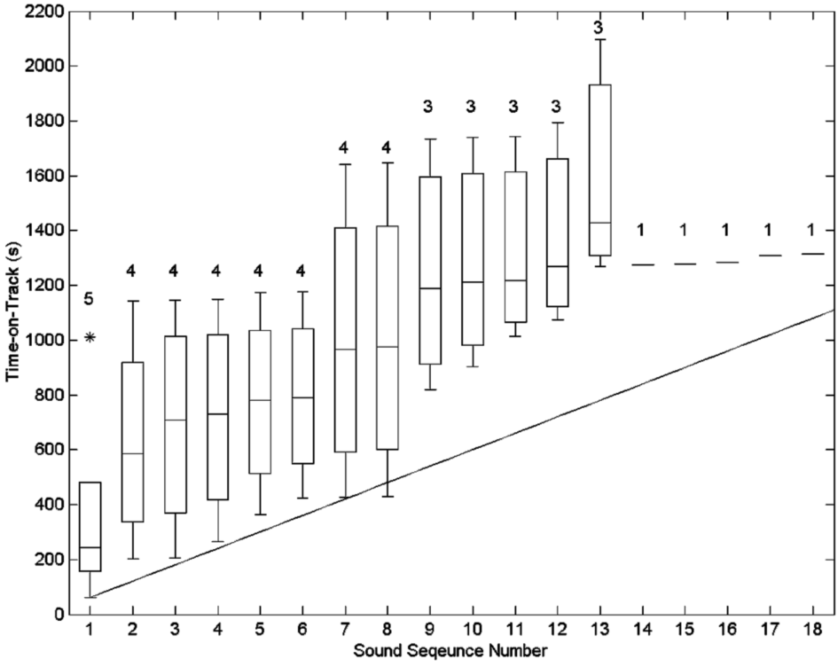

Fig. 9. Box (median, lower, and upper quartiles) and whisker (1.5 interquartile ranges and outliers *) representations of North Atlantic right-whale sound sequences and corresponding time on track (s) for all tracks where the number of sounds recorded ≥ 1. The number above each box represents the total number of tracks that contained the nth sound. The step-like pattern in the time on track of the consecutive sounds indicates a clustering of sounds though time. The solid line represents an arbitrary rate of increase of one sound per minute).

Matthews *et al.* [25], some of which were recorded in the Bay of Fundy using an on-whale hydrophone (recordings provided to us courtesy of M. Johnson, D. Nowacek, and P. Tyack, Woods Hole Oceanographic Institution, Woods Hole, MA).

Although our results are derived from a limited period (~ 2 h) of *in situ* daytime recording, a high proportion (45/53) of the sounds we recorded were suitable for analysis. The relatively low-intensity levels of the remainder or their association with high ambient noise can be attributed to a low signal-to-noise ratio. Despite these limitations, within the two hours of data collected, sounds were identified at a rate between 0.3 and 0.7 per minute, which is similar to the daytime “moan” rate of 0.8 sounds per minute for the Bay of Fundy that we calculated from Matthews *et al.* [25].

A. Mean Peak Frequency and Frequency Modulation

The majority of the right-whale sounds occurred within a relatively narrow mean peak frequency range of 300–600 Hz. Instantaneous relative-frequency variation is comparatively small in these data, about $\pm 4.5\%$ of the mean peak frequency. The dominant frequency range for similar sounds in other mysticetes is also quite narrow; Southern right whales have a dominant-frequency range similar to the sounds presented here, although slightly lower (160–500 Hz) [18]–[20]. The tonal “moans” for bowhead whales (*Balaena mysticetus*) range from 100–400 Hz [8]; this species has been the subject of numerous acoustic studies used to estimate population size and distribution [9], [10], [31]–[33]. Frequency characteristics such as range, noncontinuous narrow-band sounds, and modulation have been used in acoustic detection and automatic recognition for several baleen species [6], [34], [35], but not the right whale.

B. Duration and Clusters

The duration of right-whale sounds reported here (0.1–1.2 s; mean 0.42 s) may be shorter than the actual sounds because of the effects of noise: the “true” distribution may be less skewed to the left (fewer sounds of short duration and more of long duration and, thus, a higher mean). Nevertheless, these durations are similar to those reported for North Atlantic right whales; Matthews *et al.* [25] recently reported a range of 0.4 to 1.5 s duration for “moans.” The ~ 0.5–10-s duration estimates for low-frequency (<100 Hz) sounds [25] were not observed in our study, possibly due to the occurrence of higher noise levels below 100 Hz and our definition of duration.

Sound duration is a defining characteristic used for monitoring fin whales (*Balaenoptera physalus*) [11] and duration reliably characterizes humpback-whale (*Megaptera novaeangliae*) sounds, as cited in Mercado and Frazer [36]. The results presented here suggest that duration could represent an important characteristic to include in a recognition algorithm for right-whale sounds.

The clustering of sounds that we observed is consistent with the clustering reported by Matthews *et al.*[25] for North Atlantic right-whale sounds and clustering of sounds is a defining characteristic used in the detection of blue whales [35]. One consequence of sounds being clustered is the potential for long intervals with no sounds (e.g., as long as 16 min in the 1999 data presented here and approaching 1 h in recently collected 2000 data, unpublished), which could have implications for continuous monitoring of right whales.

C. Comparison to Southern Right-Whale Sounds

The repertoire of the southern right whale has been studied extensively (Clark [19], [20]). In general, some of the North

Atlantic right-whale sounds recorded in the Bay of Fundy were similar to those described for the Southern right [16]–[20], though there are differences. Simple frequency-modulated upsweeps with most energy in the 80–250-Hz range have been noted by Clark [14] as "contact calls" for North Atlantic right whales. Our analyzes did not reveal corresponding sounds (but see Desharnais *et al.* [26]), likely because we experienced high noise levels at these lower frequencies.

The categories of sounds documented by Clark [19], [20] for the Southern right whale do not entirely correspond to those reported here. Though our North Atlantic right-whale sounds are enveloped by the frequency ranges for "complex moans," "belch-like utterances," and miscellaneous low-frequency "phonations" of Southern right whales [17], [18], the frequencies of the primary harmonics we observed tended to be higher than the frequency of the principal energy in the sound categories reported for Southern right whales. The relatively rare sounds with fundamental frequencies <200 Hz may match Clark's "constant call" category and other sounds may match Clark's "high-calls" category (tonal sounds in the 200–500-Hz band with FM sweeps), though we did not observe the distinctively sharp and terminal-frequency downsweep.

The higher frequency (>900 Hz) sounds observed in our data (7%) may also be attributed to right whales. Southern right whales use a principal range of 50 to 500 Hz [18] but exhibit fundamental frequencies as high as 1500 Hz [16]. It is also possible that the higher frequencies we recorded were higher harmonics where the fundamental and lower harmonics were not detected. The North Pacific blue whale exhibits more energy in higher harmonics than in lower harmonics [37]. Whether the higher frequency sounds we observed were harmonics or fundamentals, they represent part of the frequency range of North Atlantic right whales.

Southern right-whales sounds have been noted as having durations ranging from 0.3–6 s [16]–[19]. Cummings *et al.* [18] observed "belch-like utterances" with an average duration of 1.4 s. Our measures of duration are comparable, if slightly shorter. We did not observe sounds of greater duration that are associated with "complex moans" [18] and "constant calls" [19] in Southern right whales.

Our estimate of sound-production rate (0.3–0.7 per min daytime) is an order of magnitude higher than the daytime rate (0.03) and comparable to the nighttime rate (1.0) reported for Southern right whales [16], though the absolute number of animals within sound range in either study is unknown. The clustering of sounds we observed is similar to that reported for the Southern right whale at night [16].

D. Summary and Conclusions

The results presented here for North Atlantic right-whale sounds in the Bay of Fundy indicate a variety of detectable underwater sounds with, in this data set, mean peak frequencies typically in the 300–600-Hz range. Frequency variation, defined as the difference between the maximum and minimum peak frequency during the sound, was found to be about $\pm 5\%$ of the mean peak frequency, on average. Harmonics were relatively rare. Sounds were typically of about 0.5 s duration. Reception rates were between 20 and 40 per hour and appear to have been clustered in time.

This study has shown that sounds produced by the North Atlantic right whales in the Bay of Fundy are detectable and contain distinct characteristics that can be quantified using the methods presented. The sounds demonstrate a range of characteristics likely typical of some proportion of the sound repertoire. Thus, it seems likely that the sounds can be used to assess the feasibility of temporal and spatial monitoring of right whales in their relatively constrained habitat in the Bay of Fundy. We are now engaged with others in ascertaining source levels and conducting hydrophone array trials that will provide further estimates of the fundamental frequencies, modulations, and duration that appear to be important characteristics for signal-identification and monitoring purposes.

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